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Critical Heat Stress Evaluation In Two Ebola Ensembles

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Critical Heat Stress Evaluation In Two Ebola Ensembles

by

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of the requirements for the degree of
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Abstract

Ebola, a type of filovirus that causes hemorrhagic fevers, dominated global headlines in 2014 when the largest Ebola epidemic in history took place in West Africa. Healthcare practitioners are at particular risk of contracting Ebola while taking care of patients with the disease because they are easily exposed to bodily fluids such as blood, urine, saliva, and feces, quite often in the intensive care unit (ICU). While personal protective equipment (PPE) protects the healthcare practitioner by providing an effective barrier against the virus, users are also at risk for heat stress. The type of protective clothing that is used as part of a PPE ensemble can affect the amount of heat stress users experience. In this study, coveralls made of monolithic barriers, which prevent vapors from escaping the suit, are compared to coveralls made of micro-porous material, which allows evaporated sweat to escape the suit. The Microgard® 2000 TS Plus, made of micro-porous barrier material and the monolithic barrier Microgard® 2300 Plus were compared against a control ensemble of work clothes consisting of a long-sleeve shirt and trouser.

A progressive heat stress protocol was used to determine the critical environment at the upper limit of compensable heat stress. The critical condition is the point at which the heat gain caused by wearing the protective ensemble as well as dry heat exchange is balanced by the maximum heat loss due to evaporative cooling. Wet bulb globe temperature at the critical condition ($WBGT_{crit}$) ,total evaporative resistance ($R_{e,T,a}$), and clothing adjustable factor (CAF) were calculated for each ensemble based on data at the critical point. Also at the critical condition, participant rectal temperature

(T_{re}) , heart rate (HR), skin temperature (T_{sk}), and physiological strain index (PSI) were noted and compared for each ensemble.

A two-way ANOVA (ensemble x participant) for $WBGT_{crit}$ and $R_{e,T,a}$ as dependent variables was used to determine whether or not there were differences among ensembles. Tukey's honest significance test was used to determine where significant differences occurred. $WBGT_{crit}$ was 33.8, 26.3, and 22.9 °C-WBGT for Work Clothes, M2000, and M2300 respectively. $R_{e,T,a}$ was 0.012, 0.031, and 0.054 kPa m^2 W^{-1} for WC, M2000, and M2300 respectively. The higher the $WBGT_{crit}$ for an ensemble, the more it can support evaporative cooling and hence the better it is at ameliorating heat stress. Based on this trial, the micro-porous ensemble Microgard® 2000 TS Plus has better heat stress performance than vapor-barrier Microgard® 2300 Plus. As expected, there were no differences for any of the physiological metrics at the critical conditions.

Chapter One:

Introduction

Ebola is a type of filovirus that causes hemorrhagic fever [1]. 2014 marked the largest Ebola epidemic in history when multiple countries in West Africa were affected. Ebola, like Hepatitis B, Hepatitis C, and Human Immunodeficiency Virus (HIV), is a blood borne pathogen that is spread through contact via blood, saliva, among other body fluids [2]. What makes Ebola a significant threat is that a small infectious dose causes an extremely infectious disease, which we currently have no cure for.

Healthcare practitioners are at particular risk of contracting Ebola while taking care of patients with the disease because they are easily exposed to bodily fluids such as blood, urine, saliva, and feces in the Intensive Care Unit through daily activities such as using needles, syringes, foley catheters, etc. Encapsulating personal protective equipment, which is equipment that is worn to minimize exposure to workplace injuries and illnesses by shielding the head and entire body has an integral role in Ebola prevention.

Major organizations such as United States Centers for Disease Control and Prevention (CDC), World Health Organization (WHO), Occupational Safety and Health Administration (OSHA) have published guidelines for selecting personal protective equipment for Ebola. Because of evolving literature as well as continual improvement in understanding of Ebola, these guidelines are constantly updated. In general, the entire body especially mucosal regions in mouth, nose, and eyes should be covered via face shield, goggles, or surgical masks with a design that does not collapse on the mouth [4]. A fluid resistant respirator that is either a N-95 or Powered Air Purifying Respirator (PAPR) should be used. If using a PAPR, choosing one with a self-contained filter and blower unit integrated within the helmet or headpiece is preferable [5]. Next, all healthcare practitioners should use double gloves made with nitrile material with extended cuffs to decrease the chances of needle stick injuries as well as contamination while removing PPE ensemble. Waterproof boots are also recommended as they help prevent needle stick injuries, are slip resistant, and easier to clean and disinfect in comparison to the combination of closed toe shoes and covers [6].

In regards to protecting the torso, a disposable gown and apron or a disposable coverall and apron combo should be worn over scrubs [6]. The decision to use a gown or coverall has been a topic of debate but there has been no literature recommending one over the other [6]. However gowns are more familiar to healthcare practitioners and easier to put on and take off. This may decrease the risk of contamination while donning and doffing PPE. On the other hand, coveralls are designed to protect the entire body while gowns leave possible openings in the back and only reach the mid-calf. In general, coveralls are made of material that do not allow as much gas exchange as gowns, thus leaving the user at greater risk for heat stress [7].

PPE allows health care workers to provide the necessary attention and care to patients suspected of having Ebola, while ideally providing re-assurance that risk for contracting the deadly hemorrhagic fever are minimal. Physicians, nurses, respiratory technicians and radiology technicians are among the healthcare practitioners that come in contact with patients the most and will require PPE. Tasks where Ebola could be spread could include intubation followed by ventilator and breathing tube management, drawing blood for labs, cleaning patient urine and feces, repositioning patients for x-rays.

The majority of patient contact occurs in the chest and torso areas as well as both arms and hands, which are both sufficiently protected by coveralls and gowns. PPE allow those involved with patient care to move and perform these tasks freely [5]. Ideally, range of motion should not be affected but those utilizing PAPRs along with coveralls may be hindered by the added bulk of the PPE. This could decrease motor function because the user may not be used to the weight of the apparatus and may lose some range of motion [7]. Furthermore, double gloves have been shown to limit the fine motor function, which results in increased movement time as well as decreased steadiness. Next, vision could also be affected by the use of respirators. Johnson et al. performed a study in 1997 that showed a decrease in visual range in subjects when respirators fog up [8]. Other issues that have occurred in subjects who have used full body PPE include anxiety due to claustrophobia, decreased comfort, decline in cognitive function, and finally heat stress [9,15].

While personal protective equipment to protect the healthcare practitioner by providing an effective barrier against the virus, users are also at risk for heat stress. This is especially true of full body ensembles, which incorporate a coverall in addition to respirators, gloves, boots, etc. [7]. Coveralls increase thermal insulation, allow for very little gas exchange, and thus limit evaporative heat loss [10]. The issue of heat stress is magnified by the tropical climate in West Africa, where the 2014 epidemic greatly affected Sierra Leone and Guinea [12]. Sierra Leone and Guinea have similar climate with high year round temperature, humidity, and rainfall. Kuklane, et al. reported that protective clothing made of an impermeable moisture outer layer could only be worn for about 40 minutes until the user’s core body temperature reaches the safe limit for occupational exposure [14,39].

Given the short duration that healthcare practitioners have while wearing protective clothing, they must either work faster and risk making medical errors or constantly doffing and donning suits in order take breaks to allow for body temperature to cool [7]. Neither option is effective because working faster places the worker at risk of incurring even more heat stress while increasing the risk of an adverse effect to patient, self, or even the rest of the healthcare team [39]. Working faster requires a higher metabolic rate and increases the risk of heat stress [7]. Moreover, by working at a rapid pace that the healthcare practitioner may not be comfortable with, he/she increases the chances of making a medical error such as accidentally extubating a patient, overlooking a change in vital signs, pushing the wrong the medication intravenously, and suffering accidental needle stick injuries.

The alternative option of abiding by the ~40 minute time frame and frequently changing in and out of PPE also has its drawbacks. Because the suits are disposable, the economic cost of going through multiple suits on a daily basis would be significant. Furthermore, from an administrative standpoint there would have to be at least twice as many healthcare personnel present during any shift when a PPE is being used in order to insure the continuity of medical care while allowing each PPE user ample time to remove PPE and take breaks to cool down and hydrate [16]. It could take 30 minutes to get fully dressed in full PPE, 30 minutes to undress, and 30 minutes for recovery between work periods [39]. Advanced suits that used personal cooling with ice or phase change materials may allow for a longer working period of closer to two hours [40]. These suits may cost at least 10 times as much per set as current coveralls, but the higher initial costs can be offset by the reusability of the suits as well as less personnel that will be necessary to be present at each workstation [39].

In addition to the economic ramifications of frequent replacements of Ebola protective equipment, there is also increased risk of opportunistic infections. The effectiveness of PPE depends on using proper technique while donning and doffing equipment. The importance of proper technique and training is underscored by the requirement of having an onsite manager/trained observer present anytime PPE is used [5]. The manager must confirm that all parts of the PPE are in working condition and the PPE must be donned in the correct order in order to ensure effectiveness [5]. Once the healthcare practitioner has entered the Ebola patient's room, the PPE may not be modified. If any part of the PPE is breached during the course of patient care, the user must immediately leave the room to return to the entry area to assess for possible exposure [5]. When the healthcare practitioner is ready for doffing, he/she must inspect and disinfect any visible contamination prior to entering the anteroom where PPE will be removed [5]. A trained observer must be present to remind the user of the proper steps of the doffing procedure as well as help remove specific components of the PPE. It is important that the PPE is removed in the correct order in order to minimize risk of cross-contamination [17]. Finally, all disposable PPE must be placed in a liquid resistant biohazard bag to be properly disposed [5].

The type of protective clothing that is used as part of a PPE ensemble can affect the amount of heat stress its users experience. In this study, coveralls made of monolithic barriers, which prevent vapors from escaping from the suit, are compared to that of micro-porous material, which allows water vapor from sweat evaporation to escape the suit. A progressive heat stress protocol was used to estimate a critical wet bulb globe temperature ($WBGT_{crit}$) at which thermal equilibrium can no longer be maintained. The protocol allowed for an estimation of total evaporative resistance ($R_{e,T,a)}$.

A clothing adjustment factor (CAF) can also be calculated from the $WBGT_{crit}$ and assigned to each ensemble.

Chapter Two:

Literature Review

Protective clothing is a part of a PPE ensemble that is worn by healthcare workers to protect themselves from the biological hazards of Ebola. In addition to protecting users from biological hazards, protective clothing has also been used for chemical and physical hazards in a various industries. When considering the type of PPE to use, one must consider the potential heat stress that the PPE could cause.

For studies on clothing ensembles, two approaches can be taken. A common approach is to create conditions of uncompensable heat stress by fixing the environmental conditions to one or more typical environments at a fixed metabolic rate [20]. The average safe exposure time and/or differences in physiological response represent the ensemble performance. An alternative approach is to determine the critical environment at the upper limit of compensable heat stress following a progressive exposure protocol that was developed at the University of South Florida. Based on the critical environment, an estimation of the total apparent evaporative resistance (Re,T,a) and the critical WBGT ($WBGT_{crit}$) can be determined [17,21]. From the $WBGT_{crit}$, a Clothing Adjustment Factor (CAF) can be assigned to the ensemble, which is the difference from the critical WBGT of Work Clothes. Both $R_{e,T,a}$ and $WBGT_{crit}$ are useful indices for the comparison of the evaporative cooling capacity of clothing ensembles [22].

There have been a series of studies conducted at the University of South Florida College of Public Health on this topic over the past 15-20 years. Caravello et al, wrote that to varying degrees, clothing affects the level of heat stress that a person experiences via convection, conduction, radiation, and most notably sweat evaporation [18]. Evaporative resistance modifies the maximum rate of evaporative cooling, and is therefore the most important factor with respect to maintaining thermal balance [19].

Wet Bulb Globe Temperature (WBGT)

The wet bulb global temperature (WBGT) is widely used in the assessment of environmental conditions to monitor for occupational heat stress [21]. WGBT is a measure of heat stress, which takes into account humidity, temperature, wind speed, solar radiation, and sun angle. The formula for WBGT in an indoor or outdoor setting with no solar load, $WBGT = 0.7T_{nwb} + 0.3T_g$. When measuring WBGT in an outdoor setting with sunlight, $WBGT = 0.7T_{nwb} + 0.2T_g.+ 0.1T_{db}$, where T_{nwb}=Natural Wet Bulb Temperature, T_g=Globe Temperature, and T_{db}=Dry Bulb Temperature [22]. Dry bulb temperature indicates the amount of heat in air and is measured by a thermometer that is shielded from moisture and direct radiant heat sources [23]. Globe temperature reflects radiant heat and is the temperature inside a blackened, hollow, thin copper globe [23]. Natural wet bulb temperature is measured by exposing a wet sensor such as a wet cotton wick fitted over the bulb of a thermometer to the effects of evaporation and convection [23].

Effects of Clothing on Evaporative Sweating

Evaporative cooling is limited by clothing, specifically total evaporative resistance ($R_{e,t,a}$), which affects the ability of the clothing ensemble to facilitate evaporative cooling. Research by Havenith et al. in 1999 showed that while convection, conduction, and radiation have minor roles in maintaining thermal equilibrium in hot climates, evaporative resistance is the most important factor because of sweating’s profound effect on cooling

[18,26]. Evaporative resistance and vapor permeability of clothing is affected by many factors including air motion, body movement, and wetness. Each clothing ensemble has a static $R_{e,t,a}$ that reflects values when clothing is worn without any significant movement in a controlled environment. A more accurate reflection of realistic conditions would be resultant values of $R_{e,t,a}$. For example, multiple studies by Lotens, Havenith and Holmer have shown that walking at a brisk pace can decrease the insulation of moderately thick clothes by nearly 50% because it helps facilitate air moving in and out of clothing [27,28]. A similar mechanism explains decreased total evaporative resistance.

Clothing adjustment factors were developed because WBGT-based assessments are based on observed (empirical) relationships and not rational (biophysical) relationships. Hence it is difficult to account for clothing effects based on insulation and evaporative resistance without having a standardized method to account for different clothing material [21]. Clothing adjustment factors (CAF) were first described by Ramsey in 1978 and further developed by Bernard, et al. and adopted by the American Conference of Governmental Hygienists (ACGIH) in 1990 [21,22]. CAFs are based on differences between the critical WBGT ($WBGT_{crit}$) of clothing ensembles of interest and that of work clothes, which serve as a baseline. The higher the $WBGT_{crit}$, the better it is from a heat stress perspective because it can support more evaporative cooling. The effective WBGT is the sum of the $WBGT_{crit}$ and CAF, and can be compared to an occupational exposure limit [21]. The critical WBGT in degrees Celsius is calculated as $0.7\ (T_{pwb} + 1.0) + 0.3\ T_g$. T_{pwb} is the psychometric wet bulb temperature which is similar to the wet bulb temperature except the measurement is taken with 3.5 meters/second of air forced across the wet cotton wick of the bulb [23].

Metabolic Rate

The metabolic rate, M has a profound effect on heat stress by increasing heat generation. Bernard et al. demonstrated this in a 2005 study when their vapor barrier Tychem QC® ensemble had a metabolic rate that was 10 W m^{-2} higher than the others. This resulted in a $WBGT_{crit}$ that was 6 to 8 °C lower than the other 4 ensembles [21]. Ashley et al. also found this inverse relationship in a 2008 study that compared three metabolic rates with five ensembles and concluded that increasing the metabolic rate decreased the $WBGT_{crit}$, while increasing the physiological data (HR, T_{re} , and PSI) [29].

On the other hand, metabolic rate has not been shown to change clothing adjustable factor, CAF. Bernard et al. investigated this in 2008 when they showed that metabolic rates approximating light, moderate and heavy work had no effect on the CAF of four clothing ensembles [19]. While the $WBGT_{crit}$ is expected to decrease with increasing M, this decrease should be the same across all ensembles, thus the CAF which is added to each to the WGBT will remain the same [22]. The CAF can be used in either low or high metabolic rates [22].

Physiological Strain Index

Moran et al. developed the Physiological Strain Index (PSI) in 1998, which is based on rectal temperature and heart rate. The PSI ranges from a scale of 0 (no strain) to 10 (very strenuous) and depicts the heat strain that is reflected by both the cardiovascular and thermoregulatory system [30]. The PSI allows for real time analysis of heat strain and can be applied at any time during both rest and recovery periods whenever HR and T can be measured [30]. Furthermore, this index can compare the strain between any combination of clothing ensemble and climate. A follow up by Moran et al. in 1999 found no gender differences in PSI between matched cohorts of males vs.

females. This same study also found that a group of fitter males and females both had a lower PSI [31].

Objective of the study

There is no current universal guideline for personal protective equipment against Ebola. Coveralls are only one aspect of PPE that healthcare personnel must wear in order to safeguard themselves when treating patients with a possible diagnoses of Ebola. In addition to considering the effectiveness of protection against the filovirus, heat stress is another major consideration. Therefore one must balance choosing an ensemble that may be more resistant to filoviruses, but run a higher risk of its users suffering heat stress disorders. The purpose of this study is to determine if there are differences in heat stress among three clothing ensembles. The $WBGT_{crit}$ and the $R_{e,T,a}$ will be integral to comparing these three ensembles under heat stress conditions

Hypothesis

Null Hypotheses:

There are no differences in heat stress and heat strain among standard work clothes ensemble (reference ensemble), MICROGARD® 2000 TS Plus and MICROGARD® 2300 Plus protective clothing when worn with facemask, hood, gloves, goggles, and boots.

Alternative Hypothesis:

There will be differences in heat stress and heat strain among standard work clothes ensemble (reference ensemble), MICROGARD® 2000 TS Plus and MICROGARD® 2300 Plus protective clothing when worn with facemask, hood, gloves, goggles, and boots.

Chapter Three:

Methods

Experimental Design

The study was a balanced cross over design. Each participant completed a trial with each ensemble. The order of ensembles was randomized in a partially balanced cross over design. Each participant served as their own control, completing trials in work clothes and the two Microgard® Ebola ensembles for a total of three trials each. $R_{e,T,a,}$, $WBGT_{crit}$, and CAF are measures of heat stress, while T_{re} , HR, T_{sk}, and PSI are measures of heat strain. All were measured and used to comparison among the three ensembles. Metabolic rate and relative humidity are controlled to avoid confounded results. In addition, metabolic rate was controlled for in the data analysis.

Participants

The University of South Florida Institutional Review Board approved the study protocol. A written informed consent was obtained prior to enrollment in the study. Participants were recruited from the University of South Florida campus via word of mouth and fliers posted in areas frequented by the target population, such as the student union, fitness center, College of Education and College of Public Health. Each participant was examined by a physician and approved for participation. A medical, family, social and work history was taken to assess current state of health and to determine that participants are healthy with no chronic disease or medication use known to influence or adversely affect thermoregulatory or cardiovascular response to heat. A physical examination for evidence of disorders of the vestibular system, pulmonary system, cardiovascular system, gastrointestinal system, genitourinary system, musculoskeletal system, and neurological system was performed and each participant underwent a resting 12-lead electrocardiogram. Inclusion criteria were males between ages 18-40 who passed the physical exam and were medically approved to participate. Participants were excluded if there was evidence of drug or alcohol abuse or use of the following classes of medication: alpha and beta (sympathetic) blocking agents, anticholinergics, antidepressants, lithium, antihistamines, calcium channel blockers, cocaine, diuretics, dopaminergics, ethanol, neuroleptics, and sympathomimetics. Subjects were also excluded if they had a history of hypertension, cardiovascular disease, heart or lung disease, renal pathology, diabetes, asthma, or previous incidence of heat injury.

Six acclimatized adult males participated in the experimental wear trials. Table 1 provides information on their physical characteristics. Participants were reminded of the need to maintain good hydration. On the day of a trial, they were asked not to drink caffeinated beverages three hours before the appointment and not to participate in vigorous exercise before the trial. Prior to beginning the experimental trials to determine critical conditions, participants underwent a 5-day acclimatization to dry heat that involved walking on a treadmill at a metabolic rate of approximately 150 W m^{-2} in a climatic chamber at 50°C and 20% relative humidity (rh) for two hours. Participants wore tee shirts, shorts, socks, and athletic shoes.

Table 1. Participant Characteristics

Participant	Age [yr]	Heigh t[m]	Weigh t[kg]	Body Surface Area [m^2]
S02	32	1.70	85	1.96
S06	23	1.72	94	2.07
S07	25	1.82	100	2.21
S08	19	1.82	76	1.97
S09	24	1.77	80	1.97
S10	25	1.92	90	2.20

Clothing

Table 2. Description of Clothing Ensembles

Clothing Ensemble	**Description**
Work Clothes	Standard cotton work clothes (6 oz. shirt and 8 oz. trousers) worn over a base ensemble of tee-shirt, shorts, socks, and athletic shoes
Scrubs	55% cotton, 45% polyester: unisex solid top-single left chest pocket, loose fitting v-neck short sleeves with side slits; unisex trousers- 1 pocket traditional boxer style with drawstring cord
M2000	MICROGARD® 2000 TS Plus worn over scrub suit and with hood, face-covering goggles, gloves and boots. (WHITE)
M2300	MICROGARD® 2300 Plus worn over scrub suit and with hood, face-covering, goggles, gloves and boots. (YELLOW)

For this study, there were three ensembles based on fabric and construction as described in Table 2. Each participant wore all three ensembles in a balanced order.

Work Clothes Scrubs Microgard® 2000 TS Plus Microgard® 2300 Plus

Figure 1: Various Trial Ensembles

Equipment

The trials were conducted in a controlled climatic chamber. The internal dimensions of the chamber are 2.7-m wide, 3.0-m deep and 2.2 m high. The possible range of environments in the climatic chamber were between 10 to 90% relative humidity (RH) and 4 to 60^{o} C. Humidity for the experimental trials was controlled at 50 % RH and air speed at 0.5 m/sec. Temperature was controlled according to protocol. The ambient environmental conditions inside the chamber were monitored using a Quest temperature monitor with measurements of the dry bulb, natural wet bulb and globe temperatures.

A motorized treadmill was used to control the metabolic rate and work demand through settings of speed and slope to elicit a target metabolic rate of 150 W m^{-2} and approximate moderate work independent of aerobic capacity.

Heart rate (HR) was monitored using a sports-type heart rate monitor (Polar Electro Inc., Lake Success, N.Y.). Rectal temperature was measured using a flexible thermistor inserted 10-cm beyond the anal sphincter muscle. Prior to each trial, the rectal thermistor was calibrated in a warm water bath. All other equipment was calibrated following laboratory standard procedures or per manufacturer's recommendations.

Skin temperatures (T_{sk}) were measured using surface thermistors taped to four sites (chest, upper arm, thigh, and calf) following the method of Ramanathan [32]. Average skin temperature was $T_{sk} = 0.3\ T_{ch} + 0.3\ T_{arm} + 0.2\ T_{th} + 0.2\ T_{calf}$. Pre-trial and post-trial weight while wearing cotton tee shirt, gym shorts, socks and athletic shoes were taken on a Mechanical Linear Beam Medical Weight Scale.

Metabolic rate was estimated from assessment of oxygen consumption (VO2) using a Douglas bag method. Expired air was collected and sampled by having participants breath through a two-way valve attached to flexible tubing that was connected to the Douglas bag. The volume of expired air was measured using a dry gas meter. A small sample was removed from the collection bag and drawn into an oxygen analyzer to determine oxygen content. Comparison was then be made between the composition of inspired and expired air, allowing VO2 to be determined.

Protocols

A progressive heat exposure protocol was used during the experimental trials. Each participant wore each ensemble as they walked on the treadmill at a moderate rate of work (150 W m^{-2}). The order of ensembles was randomized in a partially balanced design. Participant weight was recorded before the start of each trial and as well as after completion of each trial. The heart rate monitor was secured with a chest strap. The four skin surface thermistors were attached, and rectal thermistor (after insertion by each participant in a separate private dressing room) was taped to the participant's upper buttock to prevent thermistor from being pulled out during trials. During trials, participants were allowed to drink water or a commercial fluid replacement beverage (Gatorade®) at will with volume of fluid ingested recorded each hour and at the end of each trial. If the pre-trial and post-trial weights showed a net loss of 1.5% or more of body weight, participant was advised to continue aggressive fluid replacement for the remainder of the day.

Core temperature, heart rate and ambient conditions (dry bulb, natural wet bulb and globe temperatures; T_{db}, T_{nwb} and T_g, respectively) were monitored continuously and recorded every 5 minutes. Initial dry bulb temperature (T_{db}) was set according to ensemble at 36°C for work clothes, 28 °C for M2000 and 23 °C for M2300. Relative humidity (rh) was set at 50% for all three ensembles. Once the participant reached thermal equilibrium (no change in T_{re} and heart rate for at least 15 minutes.), T_{db} was increased 0.8 °C every 5 minutes.

Trials were scheduled to last 120 minutes unless one of the following criteria was met: (1) a clear rise in rectal temperature (T_{re}) associated with a loss of thermal equilibrium (typically 0.1 °C increase per 5 min for 15 min), (2) T_{re} reached 39 °C, (3) a sustained heart rate greater than 90% of the age-predicted maximum heart rate, or (4) participants experienced sustained fatigue or weakness, light-headedness, nausea, dizziness, faintness, muscle cramps, or pains in the joints or muscles, or wished to stop.

Inflection Point and Determination of Critical WGBT

The inflection point or critical condition marks the transition from thermal balance to the loss of thermal balance, where core temperature continued to rise. The chamber conditions five minutes before the noted increase in core temperature was taken as the critical condition. One investigator noted the critical condition, and a second investigator randomly reviewed the decisions. The $WBGT_{crit}$ in °C-WBGT at the inflection point was computed as $0.7\ (T_{pwb} + 1.0) + 0.3\ T_g$ [33].

Calculation of Clothing Parameters

Estimations of $R_{e,T,a}$ and $WBGT_{crit}$ follow from a progressive heat stress protocol which identifies the critical conditions at which the maximum heat loss due to evaporative cooling (vapor pressure difference between the environment [P_a] and the skin [P_{sk}] divided by the apparent total evaporative resistance [$R_{e,T,a}$]) is balanced by the net heat gain due to internal sources (H_{net}) (metabolic rate [M] less external work [W_{ext}], storage rate [S] and respiratory exchange rates by convection [C_{res}] and evaporation [E_{res}]) and dry heat exchange (for non-radiant environments, approximated by the difference between air [T_{db}] and skin [T_{sk}] temperatures divided by the resultant total insulation [$I_{T,r}$]). This relationship is demonstrated by equations 1 and 2. [18,34].

$$(P_a - P_{sk}) / R_{e,T,a} = H_{net} + (T_{db} - T_{sk}) / I_{T,r} \tag{1}$$

$$H_{net} = M - W_{ext} - S + C_{res} - E_{res} \tag{2}$$

Total static insulation ($I_{T,stat}$) values were estimated from previous data on similar ensembles. In the current study, these values were treated as a fixed value for all ensembles. The following is the process to compute derived values for each trial based on trial conditions for the participant and environment.

Resultant total insulation ($I_{T,r}$) was estimated as a two-step process according to ISO/FDIS 9920 (2007) (Equation 32) as

$$CFI = \exp[-0.281\ (v - 0.15) + 0.044\ (v - 0.15)^2 - 0.492\ w + 0.176\ w^2] \qquad (3a)$$

where air speed (v) was taken as 0.5 $m\ s^{-1}$ and walking speed (w) was the treadmill speed (m s-1) for the specific trial. This adjustment for air and body movement was similar to that proposed by Holmer et al. [28]. The value of resultant clothing insulation was further reduced by 10% (multiplied by 0.9) to account for the reduction in insulation due to wetting [36,37]. That is,

$$IT,r = CFI \bullet IT,stat \bullet 0.9 \qquad (3b)$$

Referring to Kenney, et al. (1993), the measures in Equation 2 were computed as follows. Oxygen consumption (V_{O2}, L min^{-1}) was estimated from treadmill speed (w, $m\ s^{-1}$) and clothed body weight (m_b, kg) as $V_{O2} = m_b\ (3.5 + 6\ w)/1000$. Metabolic rate (M) in $W\ m^{-2}$ was estimated from oxygen consumption in liters per minute as $M = 350\ V_{O2}/A_D$ [34]. The Dubois surface area (A_D) was calculated for each subject as $A_D = 0.202\ m_b^{\ 0.425} \cdot H^{0.725}$, where m_b was the mass of the body (kg) and H was the height (m). The external work (W_{ext}) was taken as zero because the treadmill slope was zero. Respiratory exchanges, latent respiration heat loss (E_{res}) and dry respiration heat loss (C_{res}), were calculated as $C_{res} = 0.0012\ M\ (T_{db} - 34)$ and $E_{res} = 0.0173\ M\ (5.62 - P_a)$ [35]. Kenney, et al. (1993) recognized that there might be some heat storage represented by a gradual change in T_{re}. To account for this, the rate of change in heat storage was estimated knowing the specific heat of the body (0.97 W h °C^{-1} kg^{-1}), body weight (m_b), and the rate of change of body temperature ($\Delta T_{re}\ \Delta t^{-1}$) as an average over the 20 minutes preceding the inflection point (Caravello et al. 2008). That is, $S = 0.97\ m_b\ \Delta T_{re}\ A_D^{-1}\ \Delta t^{-1}$ [18,34].

The apparent total evaporative resistance ($R_{e,T,a}$) was computed by rearranging Equation 1 to 4

$$R_{e,T,a} = (P_a - P_{sk}) / [H_{net} + (T_{db} - T_{sk}) / I_{T,r}] \qquad (4)$$

where P_{sk} was the saturation pressure of water vapor at T_{sk}.

Data Analysis

The primary dependent variables were thermal characteristics of clothing ($R_{e,T,a,}$ $WBGT_{crit,}$), and heat strain (HR, $T_{re,}$, T_{sk}, and PSI). Data were analyzed using statistical analysis software (SAS 9.4). A two-way analysis of variance (ANOVA) (clothing x participants) was used to determine if clothing ensemble had any significant effect. Tukey's multiple comparison test was used to determine where the main differences occurred. Significance was tested at the α= 0.05 level.

Chapter Four:

Results

Table 3 summarizes the metabolic rates and environmental critical conditions by ensemble. There were no differences among the three ensembles for metabolic rate normalized to body surface area (M), thus eliminating the possibility that metabolic rate could be a confounder for environmental factors at critical conditions. $WBGT_{crit}$ decreased with higher levels of evaporative resistance.

Table 3. Metabolic rate and environmental conditions at critical condition by clothing ensemble.

Clothing Ensemble	M* [$W\ m^{-2}$]	$T_{db,\ crit}$ [°C]	$P_{a,\ crit}$ [kPa]	$WBGT_{crit}$ [°C-WBGT]
Work Clothes	155 ±4	41.4 ±1.7	3.49 ±0.34	33.8 ±1.5
M2000	155 ±4	32.1 ±2.0	2.27 ±0.15	26.3 ±1.3
M2300	155 ±5	28.1 ±3.2	1.85 ±0.37	22.9 ±2.6

*No significant differences in metabolic rate.

Table 4 summarizes physiological strain for each clothing ensemble at critical conditions by ensemble. There were no differences in $T_{re,}$, HR, $T_{sk,}$, and the physiological strain index (PSI).

Table 4. Physiological strain for each clothing ensemble at critical conditions.

Clothing Ensemble	T_{re} [°C]	T_{sk} [°C]	HR [bpm]	PSI
Work Clothes	37.8 ±0.3	35.9 ±0.5	113 ±18	4.41 ±0.63
M2000	38.4 ±1.2	35.5 ±0.5	121 ±16	5.65 ±0.63
M2300	38.0 ±0.4	35.7 ±0.4	121 ±16	5.06 ±0.63

† PSI = $5(T_{re} – T_{re0})/(39.5 – T_{re0}) + 5(HR – HR_0)/(180 – HR_0)$; Where T_{re0} =36.5 and HR_0 =60

Table 5 summarizes the thermal characteristics of clothing ensembles. The static insulation $I_{T,stat}$ values were estimated from previous data on similar ensembles, and were treated as a fixed value for all ensembles. The resultant $I_{T,r}$ values were estimated according to the ISO/FDIS 9920 formula, which takes into consideration the air speed, walking speed, and adjusts for air and body movement [37]. The control work clothes ensemble had the lowest evaporative resistance and the two Microgard® ensembles both had higher evaporative resistances.

Table 5. Thermal characteristics of the clothing ensembles.

Clothing Ensemble	$I_{T,stat}$ [m^2 °C W^{-1}]	$I_{T,r}$ [m^2 °C W^{-1}]	$R_{e,T,a}$ [m^2 kPa W^{-1}]
Work Clothes	0.18	0.106	0.0112 ±0.002
M2000	0.20	0.118	0.031 ±0.006
M2300	0.20	0.118	0.054 ±0.015

*All ensembles were different from each other for the total apparent evaporative resistance and insulation.

Table 6 summarizes the wet bulb global temperature at critical conditions with resulting clothing adjustment factor for the three ensembles. Not surprisingly, the $WBGT_{crit}$ was highest for the control group and decreased with increasing evaporative resistance values. The clothing adjustment factor was calculated to depict the differences in wet bulb globe temperature and showed that CAF increased as the $WBGT_{crit}$ decreased.

Table 6. Results of multiple comparison tests for the ensembles for WBGTcrit and Re,T,a.

Clothing Ensemble	$WBGT_{crit}$ [°C-WBGT]	CAF [°C-WBGT]	$R_{e,T,a}$ [m^2 kPa W^{-1}]
Work Clothes	33.8	0	0.0112 ±0.002

M2000	26.3	7.5	0.031 ±0.006
M2300	22.9	11	0.054 ±0.015

*All ensembles were different from each other for the three metrics of thermal characteristics of study

Where the pooled Standard Error of Estimate (SEE) of the mean values is 0.77 for $WBGT_{crit}$ and 0.004 for $R_{e,T,a}$

Chapter Five:

Discussion

The $WBGT_{crit}$ and the and $R_{e,T,a}$ are dependent variables that are center to addressing our hypothesis that there will be differences in heat stress among standard work clothes ensemble, MICROGARD® 2000 TS Plus and MICROGARD® 2300 Plus protective clothing when worn with facemask, hood, gloves, goggles, and boots.

The total evaporative resistance for work clothes of 0.012 kPa m^2 W^{-1} was similar to work clothes values that were found in previous studies of 0.016 kPa m^2 W^{-1} by Kenney et al. in 1993, 0.013 kPa m^2 W^{-1} by Barker et al. in 1999 and Caravello et al, and most recently 0.011 kPa m^2 W^{-1} by Fletcher et al. in 2014 [10,18,34]. This similarity in our work clothes control ensemble total evaporative resistance with prior studies confirmed the validity of this current set of data. Moreover, the small standard deviation of 0.002 kPa m^2 W^{-1} demonstrates the reliability of our data. This is significant because the total evaporative resistance has the potential to be influenced by a series of potential errors, including the precision of knowing environmental conditions, inaccurate mean skin temperature measurements, faulty metabolic rate due to errors in estimation of respiratory heat exchange, and the presumption that a treadmill set to zero slope will not add any external work [18]. At the root of calculating total evaporative resistance is the principal that the ability of the clothing ensemble to allow thermal equilibrium at the upper limits of compensable heat stress (critical condition) affects how much the vapor pressure and dry bulb temperature changes at the inflection point (5 minutes before critical condition). It is reassuring to know that despite these many steps where errors could have occurred during our calculation of total evaporative resistance, our data were similar to that found in 4 prior studies which used the heat stress protocol at USF.

The $R_{e,T,a}$ was 0.031 kPa m^2 W^{-1} for our microporous M2000 TS Plus ensemble, which is composed of micro-porous material and was expected to have a lower evaporative resistance than vapor-resistant material. Prior studies on the NexGen® micro-porous film Bernard et al. in 2005 and Caravello et al. in 2008 yielded $R_{e,T,a}$ values of 0.036 kPa m^2 W^{-1} which is similar to our value of 0.031 kPa m^2 W^{-1} [18,21].

The $R_{e,T,a}$ 0.053 kPa m^2 W^{-1} for M2300 Plus, which is composed of polyethylene, a vapor barrier material. Caravello et al. found a $R_{e,T,a}$ of 0.029 kPa m^2 W^{-1} in a Tychem® QC Coverall [18]. Fletcher et al. found a $R_{e,T,a}$ of 0.029 kPa m^2 W^{-1} in a Tychem® F Coverall that was worn with hood and full-face respirator [10]. In that study, she noted that usage of respirators had a negligible effect on apparent total evaporative resistance, which lends further credence to our value of 0.031 kPa m^2 W^{-1} . Fletcher et al's lower value could be due to the stiffness of their ensemble that helped create a bellows effect with movement and thus higher rates of convection, although she concluded that it is difficult to know for sure how much the stiffness contributed to the evaporative resistance values that they obtained. The M2300 Plus ensemble also provided more seals than both the Fletcher Tychem® F and the Caravello Tychem® QC ensembles. Furthermore, the Tychem® QC ensemble was more compliant and moved more easily with the body. These are reasons why both Tychem® had lower $R_{e,T,a}$ values than the M2300 Plus.

Our data showed that there is an inverse relationship between $WBGT_{crit}$ and $R_{e,T,a}$. This is shown in Table 6, where Work Clothes Ensemble had the highest $WBGT_{crit}$ at 33.8 °C, while the M2000 had a $WBGT_{crit}$ of 26.3 °C, and the M2300 had a $WBGT_{crit}$ of

22.9 °C. This decrease in $WBGT_{crit}$ with an increase in $R_{e,T,a}$ was also seen in prior studies by Caravello and Fletcher and shows that the $WBGT_{crit}$ and hence heat stress is adversely affected by the increased evaporative resistance of a clothing ensemble. This is because sweating is a significant mechanism of heat loss and plays an integral role in the body's ability to thermoregulate in response to extreme working conditions.

The clothing adjustable factor (CAF) is a way to conceptualize the added thermal burden of a clothing ensemble in comparison to its control. As previously mentioned, CAFs are based on differences between the critical WBGT ($WBGT_{crit}$) of clothing ensembles of interest and that of work clothes control, which has a CAF of 0. Our data in Table 6 shows that the CAF is 7.5 for M2000 and 11 for M2300. These values are similar to the CAF's obtained in prior studies where Bernard in 2005 and Caravello in 2008 found that the Tychem® QC ensembles that were worn without a hood had a CAF of 7.8 [18,21]. The addition of a hood would be expected to add a CAF of about 1.0 so theoretically the Tychem® QC ensemble, should have a CAF of about 9 if worn the same way that the Microgard® ensembles were worn. Fletcher found that the Tychem® TAP Coverall ensemble used in her study had a CAF of 10 which makes sense because there was a double layer of material used in her study [10]. The Microgard® 2300 Plus had the highest CAF at 11, which could be due to more seals, resulting in less convective heat loss.

The final aspect of our study investigated physiological data for subjects while wearing the three ensembles. A two way ANOVA was used to evaluate whether or not the HR, Tsk, Tre, and PSI is statistically different among the three ensembles. Table 4 shows no difference in HR, Tsk, Tre , and PSI for the subjects in each of the ensemble groups. This was no surprise, prior studies by Ashley et al. in 2008 and Fletcher et al. in 2014 found no significant differences in PSI among different ensembles, and our results were consistent with this [10,29].

Limitations

The small sample size that involved only 6 college aged males could mean that there is possibly selection bias. However, the data that was collected is reliable and therefore internally valid because each subject served as his control after undergoing a standard acclimatization period prior to the trial. Moreover, the heat stress protocol that was has been previously used in several other studies conducted at the University of South Florida in the past, and thus has been fine tuned to generate reliable and valid data. The data that was collected for the control work clothes ensemble was similar to work clothes ensemble data from prior studies, which helps lend credence that the results are reliable.

There may be concern that no females were included in this study because a prior study by Ashley et al. in 2008 demonstrated that women demonstrated a higher PSI [29]. It is important to note that the increased PSI did not result in significant differences in resulting $WBGT_{crit}$. Hence, the CAF that were calculated for the Microgard® ensembles in this study would still be valid when women wear the ensembles, even if they theoretically may have a higher PSI. Next, the average age of our subjects (24.6) is almost guaranteed to be lower than the average age of healthcare personnel who would be utilizing these ensembles to treat Ebola patients. Several studies, including one by Pandolf, et al in 1997 have shown an increased susceptibility to heat stress in patients with chronic debilitating diseases, specifically heart disease [38]. Naturally there is concern that a healthy worker effect could occur in this study because our subjects are healthy college aged students. However, one should take into consideration that nurses, physicians, respiratory techs, and other potential users of

Ebola personal protective equipment should be healthier and in better shape than the general population. Therefore the young average age of subjects in our study should not decrease external validity of this study.

Conclusion

Based on the results of this study, the MICROGARD® 2000 TS Plus has a better heat stress profile than the MICROGARD® 2300 Plus ensemble. While the MICROGARD® 2300 Plus ensemble is composed of polyethylene material which is theoretically stronger than the MICROGARD®2000 TS Plus, it is unclear whether this is significant when it comes to protection against Ebola. Other considerations in the choice of fabric include, cost, style, and personal preference.

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